BIOLOGICAL PATCHINESS IN RELATION TO SATELLITE THERMAL IMAGERY AND ASSOCIATED CHEMICAL MESOSCALE FEATURES

Ronald Wayne Phoebus

NAVAL POSTGRADUATE SCHOOL
Monterey, California

THESIS

Biological Patchiness in Relation to
Satellite Thermal Imagery and Associated
Chemical Mesoscale Features

by

Ronald Wayne Phoebus

June 1981

Thesis Advisor: Eugene D. Traganza

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Biological Patchiness in Relation to Satellite Thermal Imagery and Associated Chemical Mesoscale Features

by

Commander Ronald Wayne Phoebus
United States Navy
B.S., United States Merchant Marine Academy, 1967

Submitted in partial fulfillment of the requirements for the degree of

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I. INTRODUCTION

Biological patchiness, or spatial heterogeneity, can occur on nearly every scale. The presence of biological patches, or communities, can have a direct effect on Naval operations, scientific research, and fisheries. The impact on Naval operations is apparent in the negative effects randomly distributed populations may have on sonar operations due to varying degrees of sound scattering and reverberation. Patchy distributions of plankton populations may hamper research efforts through the introduction of sampling errors into collecting efforts (Wiebe, 1971). The presence of phytoplankton populations provides pasture for herbivorous zooplankton which lure larger carnivores sought by the fisheries. A better knowledge of the cause and effects of plankton patchiness may aid man in exploiting, or perhaps avoiding, its far-reaching effects.

Prior to the turn of the century, scientists had already observed a spatial heterogeneity, or patchiness, in oceanic plankton populations. In the few decades leading up to the 1930's, the general opinion was that patchiness was attributable to heavy differential grazing of herbivorous zooplankton, thereby establishing the frequently observed negative correlation between zooplankton and phytoplankton populations. Hardy and Gunther (1935) advanced the theory that diel migrations

of zooplankton through vertical current strata could account for separation and redistribution of planktonic populations. A little more than a decade later, the now familiar negative correlation in populations was observed after only a few days of moderate grazing (Riley and Bumpus, 1946).

The end of the decade found physical oceanographers attempting to explain the phenomena whose evolution had eluded biologists for more than half a century. Stommel (1949) proposed a hydrodynamic model of plankton distribution based on Langmuir spirals in the surface waters which caused an aggregation of plankton within alternating regions of convergence and divergence. The classical work of Kierstead and Slobodkin (1953) addressed the influence of physio-chemical characteristics of the water mass, such as temperature, salinity, dissolved oxygen, and dissolved nutrients. Cassie (1959, 1960) related abundance and distribution in terms of gradients of physical factors and suggested that these factors could influence distribution patterns as much as biological interactions. Others stressed biological interaction and association as the dominant factors involved (Bernhard and Rampii, 1965). Wiebe (1970) defined patchiness as any concentration of individuals exceeding the central value in a given data set. He further subscribes to the theory of temperature, salinity, and light concentrations as primary causal factors in determining distribution. Perhaps one of the most significant contributions

was his forthright admission that patch-forming mechanisms are not well known.

The literature of the 1970's found oceanographers and biologists presenting varying hypotheses to explain spatial heterogeneity of plankton. Platt (1972) suggested distribution was largely controlled by turbulence and not the dynamic attributes of the organisms. Other scientists indicated that distribution might be attributable to local variations in the physio-chemical characteristics of the medium, or to differences in the social behavior of organisms (Platt and Filion, 1973). Kamykowski (1974) suggested observed distributions were caused by internal waves of tidal period impinging on continental shelves. These internal waves, combined with the diel migrations through levels of varying currents, could produce a horizontal separation and an inverse relationship between zooplankton and phytoplankton. Reasoning has now completed a full cycle since Hardy and Gunther proffered their hypothesis in 1935.

Riley (1976), referring to the work of Kamykowski, calls it the first and only creditable theory to explain plankton patchiness on the basis of physical forcing mechanisms. Riley, however, states that Kamykowski's theories are applicable only in waters of sufficiently shallow depth to be affected by these waves. The theory leaves unexplained the distributions observed in deeper oceanic waters. Platt and Denman (1975) offer horizontal diffusion rates and net rate of biological

change as the forcing mechanisms in these waters. Migrations of organisms combined with differential currents in the vertical as additive and subtractive quantities to tidal currents were offered to fill the voids left by Kamykowski's theory (Riley, 1976). According to Therrault et al (1978), the spatial patterns are a function of physical processes and differential algal growth rates under varying local physical conditions.

The author believes that Stavn (1971) summarized the hypotheses of nearly a century of researchers in an admirable way. He states that the principal factors determining non-random distributions of planktonic organisms may be summarized as follows:

1. Physical/chemical boundary conditions, including light, temperature, and salinity gradients.
2. Advective effects as in wind and water transport, including small scale variations due to turbulence.
3. Reproduction rates within the populations.
4. Social behavior within the populations of the same species.
5. Coactive factors determined by competition between species.

The physio-chemical and behavioral factors listed above are presumed to be continually present within a community. Large scale water mass transport may account for large scale distributions such as those found in more productive regions

of upwelling on the western coasts of continents. Spatial distribution of plankton patches are, however, frequently many orders of magnitude smaller than the oceanic gyres associated with these regions. The purpose of this study was to show, firstly, that chemical mesoscale features innoculate surrounding oceanic waters with properties sufficient, and necessary, to support biological communities, thereby establishing biological patchiness. Secondly, these mesoscale features can be observed, tracked, and geographically located through the use of high-resolution visual and infrared satellite images.

II. METHODS AND MATERIALS

Four cruises were conducted aboard the R/V Acania of the Naval Postgraduate School between April and September, 1979. The areas of interest were located in the oceanic waters off Point Sur, California. Very high resolution (1.1 km, 0.5°C) infrared and visual satellite images provided by Mr. Larry Breaker, National Environmental Satellite Service (NESS), Redwood City, California, were used to initially detect the presence of mesoscale (10 to 100 km) thermal features. When the image revealed the existence of an oceanic thermal feature, direct telephone contact was made with Mr. Breaker who provided up-to-date information relative to geographic location, intensity, and persistence of the feature as inferred by image analysis. Once a significant feature was evident, cruise preparations began and the feature was monitored by NESS. A final update with respect to geographic location was obtained just prior to the Acania's departure from Monterey. Time enroute was spent in equipment checkout and in planning the ship track. Nearing the last reported location, a constant watch was kept on sea surface temperature in order to identify thermal gradients characteristic of these features. Once detected, an appropriate search pattern was initiated to obtain maximum data density while attempting to define the boundaries of the features.

To effectively describe the relationship between chemical mesoscale and microplankton in the surface layer of the feature, it was decided to sample several significant physical, chemical, and biological parameters. To this end, continuous measurements of sea surface temperature (injection temperature, expendable bathythermographs, and bucket temperatures), dissolved nutrient (nitrate and phosphate), and biomass (adenosine triphosphate and chlorophyll fluorescence) were made.

A. CHLOROPHYLL

The relatively low concentrations of chlorophyll encountered in the surface layer (<1 μg/l) and the size of the features being investigated required a method of chlorophyll determination which was rapid, sensitive, and continuous (Yentsch and Menzel, 1963). Early investigators (Richards and Thompson, 1952) used spectrophotometric measurements of algal extracts to determine chlorophyll concentrations. More recent studies have shown that the measurement of fluorescence of chlorophyll is more sensitive than previously used methods and can be adapted to continuous *in situ* analysis (Lorenzen, 1966). The lower limit for detection of chlorophyll by fluorescence methods is about 0.1 μg/l chlorophyll *a*, which is about 5% that required by spectrophotometric methods (Holm-Hansen, et al, 1965).

Seawater for all shipboard analysis was initially pumped from a through-the-hull fitting, utilized for engine cooling (depth of 2.5 m), directly to the vessel's dry laboratory. The seawater was directed into a Turner Model III fluorometer

fitted with a flow-through cuvette. The cuvette was acid washed (1N HCl) and thoroughly rinsed with distilled water prior to each cruise, although no evidence of algal growth was ever seen. Bubble contamination, due to rough seas on some cruises (August and September) required subsequent incorporation of a bubble trap into the intake system prior to the introduction of seawater into the fluorometer. Continuous *in situ* chlorophyll fluorescence was recorded by connecting the 0 to 10 mv output terminal of the fluorometer to a suitable continuous feeding strip chart recorder. Fluorescence was calibrated by the analysis of discrete chlorophyll samples (three replicate samples) withdrawn from the fluorometer discharge outlet at one-half hour intervals throughout the cruise tracks. Additional discrete samples were drawn when significant gradients of thermal or nutrient properties were observed. Phytoplankton was harvested by filtering the replicate samples of fluorometer discharge through glass fiber filters (Whatman GF/C, 4.25 cm dia., pore size 0.45 μm) which had been moistened with a 1% solution of $MgCO_3$ to prevent premature acidification. Filters were then folded in half and placed in sterile plastic bags which were properly identified and indexed with the strip chart. The filters were immediately placed in a shipbpard freezer to await extraction in a shore laboratory facility. Holm-Hansen (1978) reported no detectable loss of chlorophyll after frozen storage for periods up to three weeks duration.

In every case reported in this study, the extraction process was completed within that period.

The chlorophyll extraction was accomplished by introducing the frozen unground filters into 15 ml screw-top centrifuge tubes containing approximately 10 ml of 90% spectral quality acetone. The tubes were vigorously shaken and placed in a darkened refrigerator for twenty-four hours. When extraction time exceeds a few hours, there is no difference between samples which have been extracted with or without grinding (Holm-Hansen, 1978). Prior to fluorometric determinations, the samples were removed from the refrigerator and brought to room temperature inside a darkened cabinet. Acetone volume was then brought to exactly 10 ml. Samples were again shaken and centrifuged at 15,000 X g for about five minutes. The fluorometer was zeroed by placing a disposable culture tube containing only 90% acetone into the light path of the fluorometer. The extractant was carefully decanted into similar culture tubes and placed in the fluorometer. Only door "slit width" settings 3 and 10 were utilized due to the non-linearity of response associated with the larger "slit" setting of 1. Each sample was removed from the fluorometer and injected with two drops 1N HCl, gently mixed and allowed to stand for one minute prior to being replaced in the fluorometer. Fluorometer readings were carefully recorded before and after acidification. Chlorophyll concentration for strip chart calibration was calculated in the manner of Strickland and Parsons (1972).

The author acknowledges more recent advances in methodology associated with chlorophyll determination. The use of pure methanol as an extraction fluid (Holm-Hansen and Rieman, 1978) and injection of DCMU (3-(3,4 dichlorophenyl)-1,1-dimethylurea), a herbicide, to block photosynthetic electron transport and thereby maximize fluorescence (Slovacek and Hannan, 1977) should be considered by future investigators. For the purpose of maintaining continuity, the procedures previously described were utilized in the determination of chlorophyll fluorescence throughout the course of this study.

B. NUTRIENTS

A Technicon Autoanalyzer II was used to measure reactive dissolved nutrients as described by Nestor (1979). Data collection was accomplished by fellow students (Conrad, 1980) involved in the Chemical Mesoscale Project at the Naval Postgraduate School.

C. ATP

A determination of adenosine triphosphate (ATP) in the particulate matter of seawater is of value as an indication of the quantity of living material (Strickland and Parsons, 1972). Seawater samples for analysis were obtained every ten minutes (ca 3 km) along the cruise tracks. Analysis techniques were those of Holm-Hansen (1972).

D. TEMPERATURE

Sea surface temperature was sensed by a thermistor located in the engine cooling water intake at the same depth, and in line with, tubing supplying seawater for all onboard analysis. Temperature was continuously recorded on a strip chart which provided a real-time visual signal of thermal gradients. Strip chart calibration was provided by periodic comparison to mercury thermometer reading and frequent expendable bathythermograph (XBT) launches.

III. RESULTS

Data presented in this study were collected between April and September 1979, during cruises of the R/V Acania. Data traces of temperature, dissolved nutrients, and biomass indicators (ATP and Chlorophyll) are plotted against elapsed distance (in km) along the respective cruise tracks. ATP and Chlorophyll a have been converted to carbon units to facilitate comparison (Conrad, 1980).

A. APRIL CRUISE

On 10 April 1979, satellite imagery showed a wave-like perturbation on a narrow band of cooler coastal water near Point Sur, California (Plate 1). On 17 April, the feature had grown, extending nearly 100 km to seaward, and had developed a noticeable cyclonic swirl (Plate 2). The following day (April 18), growth continued and the cyclonic pattern persisted with noticeable thermal banding present (Plate 3). At the same time, a similar perturbation which spawned the feature under investigation became evident in the waters north of Monterey Bay. Images received on 19 April showed little change in the feature's basic structure. The feature was persisting with, perhaps, a somewhat tighter curvature indicated (Plate 4). The perturbation north of Monterey seemed to be following the same developmental pattern of growth, cyclonic swirling, and thermal banding.

Vessel scheduling did not allow getting underway while the characteristics of these features appeared to be so well delineated. Satellite images were not available during the next several days due to cloud cover over the coastal regions of Central California. On 29 April (the first day of the cruise) images received indicated a relaxation of the previously observed swirling which appeared to recede into coastal waters with a southwesterly excursion of cooler waters (Plate 5). The Acania got underway on 29 April to investigate the remnants of the feature which had been first observed on 10 April and whose development had been monitored for more than two weeks. Figure 1 depicts the cruise track. ATP, chlorophyll a, and sea surface temperature were collected and displayed in Figures 2 and 3. Excellent agreement between thermal structure inferred from satellite imagery (0.5 cm) and sea surface temperature measurements (2.5 m) was evident. Figure 2 shows a strong inverse relationship between dissolved nutrients and temperature, presumably attributable to upwelling origins of the water mass. Peaks in biomass indicators (ATP and chlorophyll a) occurred adjacent to increases in dissolved nutrients and in regions of increasing temperature (Figure 3).

B. JUNE CRUISE

The June Cruise was of short duration to investigate a "feature of opportunity" which became visible on images received after an extended period of cloud cover that had precluded earlier reception of satellite images. Infrared images

received on 13 June revealed an intense protrusion of coastal upwelling off Point Sur (Plate 6). The R/V Acania departed Monterey to locate the feature at approximately 1800 LST and followed the track depicted in Figure 4. Figure 5 further substantiates previous findings. Nutrients and temperature again showed a strong inverse relationship, while biomass indicators peaked in areas adjacent to these maxima in warmer temperature gradients on the equatorward side of the feature. Although short in duration, the cruise provided excellent data from which to investigate the characteristics of the feature.

C. AUGUST CRUISE

Satellite images of 30 July (Plate 7) revealed a large area of apparent upwelling southwest of Point Sur. Subsequent images (5 August, Plate 8), although somewhat contaminated with cloudiness over the coastal region, showed an elongated extension of cold water projecting nearly 150 km in a south-westerly direction. Additional imagery was not available.

The cruise began on 7 August and endeavored to locate and study the feature last observed on 5 August. The cruise track followed over the next two days is shown in Figure 6. Concentrations of all sampled variables were, for the most part, quite low. The data presented in Figures 7 and 8, although sporadic, were consistent with that previously observed. Chlorophyll data became increasingly unreliable due to bubble contamination resulting from air ingestion during roughing

seas. Despite difficulties, biomass data (Figure 8) supports distributions found during previous cruises. Except for two peaks in ATP (ca 320 km and 380 km) which occur in areas of decreasing temperature, the biomass indicators were again found adjacent to nutrient maxima and in regions of increasing temperature, thereby supporting previous findings.

D. SEPTEMBER CRUISE

The satellite images of 23 September (Plate 9) showed a narrow coastal band of upwelled water extending nearly 200 km south from Monterey Bay. More intense upwelling, indicated by lighter grey shades, appeared due west of Point Sur. The next day (24 September) the upwelling previously noted west of Point Sur appeared to be more diffuse and widespread, extending approximately 70 km seaward (Plate 10). Although imagery was badly contaminated, there appeared to be a slight anticyclonic (northward) curvature associated with the feature. On 25 September, the diffuse nature and northward turning of the seaward extremity were again apparent (Plate 11). Also visible was a new, intense upwelling event positioned between Point Sur and Point Pinos. Clear images on 26 September (Plate 12) showed continued development of the latter feature within the confines of the original feature observed in earlier images. A pronounced cyclonic "hook" was developed at a position approximately 22 km off Point Sur.

The cruise began on 26 September and followed the track of Figure 9. Data presented in Figures 10 and 11 consistently

revealed the expected inverse relationship between temperature and nutrients. Biomass indicators were consistently low. The near absence of chlorophyll a in the presence of nutrient concentrations was somewhat disquieting. The only peak of consequence occurred at approximately 220 km elapsed distance in a region of relatively high nutrients and of little thermal gradient. The absence of notable chlorophyll concentrations suggested a malfunction of sampling equipment. Post cruise analysis, however, disproved this possibility. Of particular interest was the absence of biomass peaks heretofore found in the warm water gradients following nutrient increases.

IV. DISCUSSION

If one accepts Wiebe's definition of patchiness (i.e., any concentration of individuals exceeding the central value in a data set), then the results of this study stand alone as evidence that biological patchiness occurs in association with chemical mesoscale features.

Kamykowski (1974) attributed patchiness to the transport of plankters and nutrients by internal waves. Water particle trajectories in his mathematical model described ellipses of varying proportions, oriented perpendicular to the coast. Such motion in an area of intense upwelling and high productivity would allow for the wholesale transport of chemical properties and planktonic communities on a grand scale. A nutrient-rich, highly productive "blanket" of surface water would extend seaward from areas of intense upwelling. Such a large-scale transport would require a redefining of patchiness; viz., any area where concentration is significantly less than the central value of a data set. Patchiness would be indicated by voids or "holes" in the "blanket," presumably a result of grazing or other physical processes working on a smaller scale. This clearly is not the case, as further evidenced by the data traces of variables samples during this study. Large-scale water and wind transport can be similarly discounted by applying the same arguments.

It is necessary to be acquainted with the physical characteristics of the region under investigation prior to offering an alternative hypothesis. The oceanic environment off the Central California coast is largely under the influence of the California Current which marks the eastern extremity of the North Pacific Gyre. It is characterized by a general southerly flow of Subarctic Water. The current is wide (ca 700 km) with a mass transport of approximately 10 sverdrups. This transport, when considered in conjunction with the enormous width, provides for relatively slow currents as it moves sluggishly to the southeast. The waters are characteristically low in salinity and dissolved nutrients. In the spring and early summer (March to July) north-northwest winds prevail off the California coast, giving rise to upwelling that is more or less continuous throughout the period. Sverdrup (1942), in citing the work of Scripps Institution of Oceanography, shows that from areas of intense upwelling, tongues of water of low temperature extend in a southward direction away from the coast. These tongues are separated from each other by similar tongues of higher temperature water extending towards the coast. Within the tongues, the flow of warm water is directed to the north, whereas the flow of the cooler water is soughward (Figure 12).

The shear due to the opposing flow may impart positive (cyclonic) vorticity to the waters creating "swirls" and mesoscale features possessing the cyclonic curvature and thermal

banding evidenced in this study. The cold water, presumably of upwelling origin, is rich in nutrients and may carry a biological "seed" population. Once formed, the feature may be advected by the mechanism of Kamykowski or others.

As advection continues, the longevity of the feature, and indeed its populations, are further modified by chemical, physical, and physiological processes. Nutrient-rich surface waters are depleted by mixing, further advection, and assimilation by the exponentially growing phytoplankton population. Phytoplankters are lost due to turbulence, herbivorous grazing, natural aging and sinking of senescent cells.

The tendency of the biomass indicators sampled in this study to be distributed adjacent to increased nutrient concentrations but in regions of warmer temperature gradients is unexplained. The author suggests the distribution may be attributed to physiological adaptation of the plankters. Since extensive quantitative biological sampling was not undertaken, the hypothesis cannot be substantiated. The theory is plausible, as reported by Hand et al (1965). Their data suggests that with Gonyaulax polyedra (a dinoflagellate producing "red tides"), cells exposed to a 2^{o} temperature change over a 30 minute period do not lose motility, but steeper gradients do lead to paralysis. The low chlorophyll a concentrations in the presence of nutrients during the September cruise may be indicative of a new upwelling event which

was either devoid of a "seed" population, or contained a population that had inadequate time for growth, or one in which some other limiting factor was operating. Alternately, a subsurface chlorophyll concentration may have been present and undetected. Hobson and Lorenzen (1972) showed that chlorophyll maxima were associated with pycnoclines at various depths and that increased concentrations of micro-zooplankton were associated with these maxima. Subsurface maxima may also be attributed to photosynthetically active cells which are apparently adapted to low-light intensity (Andersen, 1969). Organisms may be further stressed or limited by chemical properties such as pH and dissolved oxygen. The limited variables sampled in the surface (2.5 m) layer and the absence of quantitative biological sampling again precludes substantiation in this study. These possibilities, however, should not be excluded in future research efforts.

V. CONCLUSIONS

The great impact of upwelling on the physical and econmical endeavors of man has led to extensive investigation of this phenomenon with the objective of predicting the occurrence or intensity of upwelling events. Owing to their complexity, it is doubtful that accurate prediction equations will evolve in the near future. This study has shown, in part, that remote infrared satellite sensing may be used as a real-time tool to accurately locate thermally and biologically significant features. It is possible to observe, track, geographically locate and study upwelling pulses depicted in infrared satellite images, thereby eliminating the expense of multiple ship operations in research efforts--efforts whose potential value was realized by Armstrong et al (1967).

Several signifcant physical, chemical, and biological parameters were sampled in the surface layer of the mesoscale thermal features which were located using satellite imagery. The results of biochemical sampling produced replicate results from which the distribution of biomass within the chemical mesoscale feature could be inferred. As for the causes of the observed distribution, it would be a gross simplification to segregate a single variable as the primary causal factor. This is especially valid when one deals with two media (air-sea) that are so dynamically interrelated. Theories were

advanced which most closely support the findings of Barnes and Marshall (1951), who suggested that population changes were associated with different water masses that maintained their identity while the populations developed, and the association is maintained. The biological significance of the observed spatial structure is not readily apparent and probably will not become so until patch forming mechanisms are better known (Wiebe, 1970). As research is continued, a more explicit relationship between the physical, chemical, and biological processes will no doubt emerge.

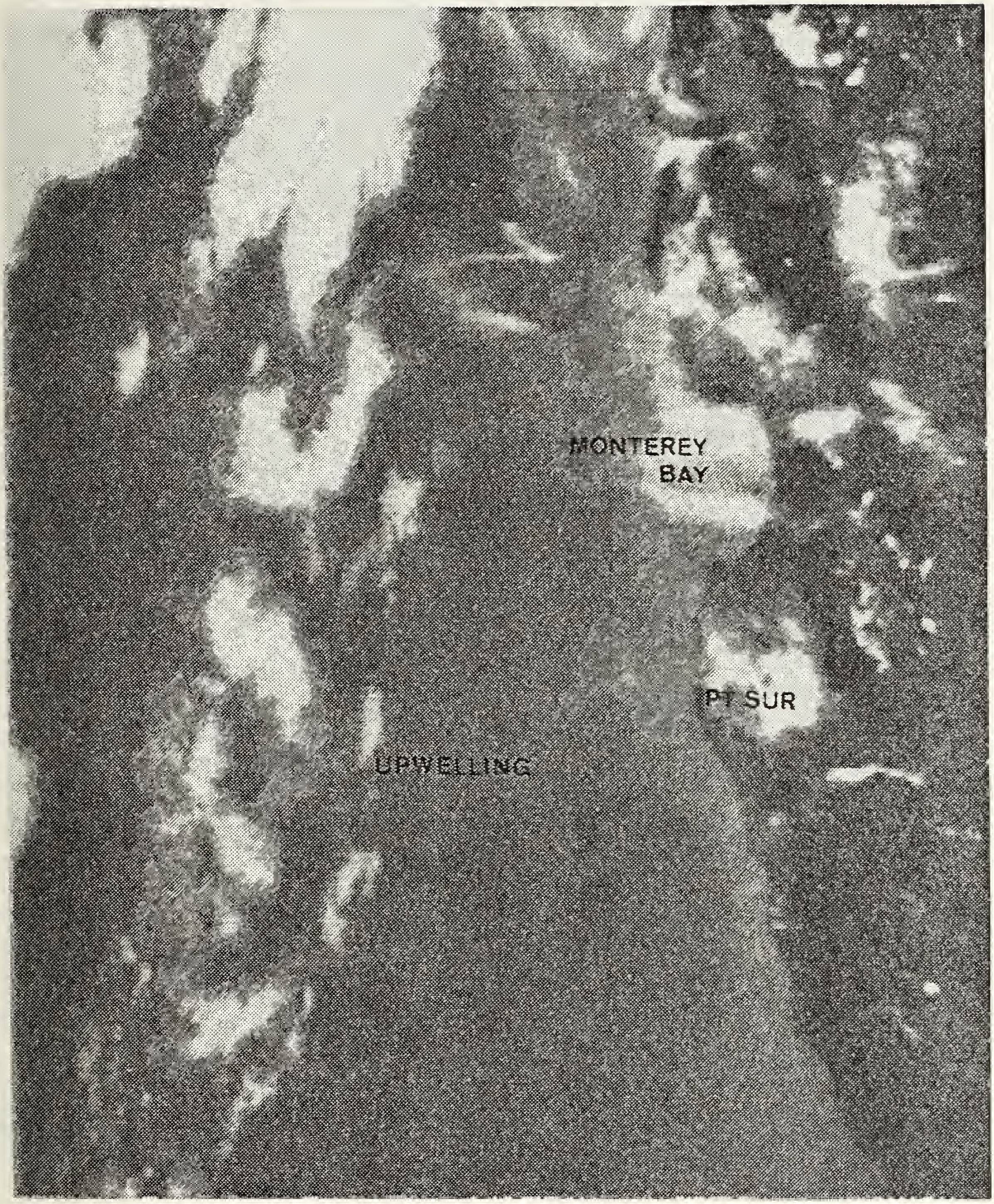

Plate 1. TIROS-N Satellite IR Image of the California Coast, 10 April 1979.

Plate 2. TIROS-N Satellite IR Image of the California Coast, 17 April 1979.

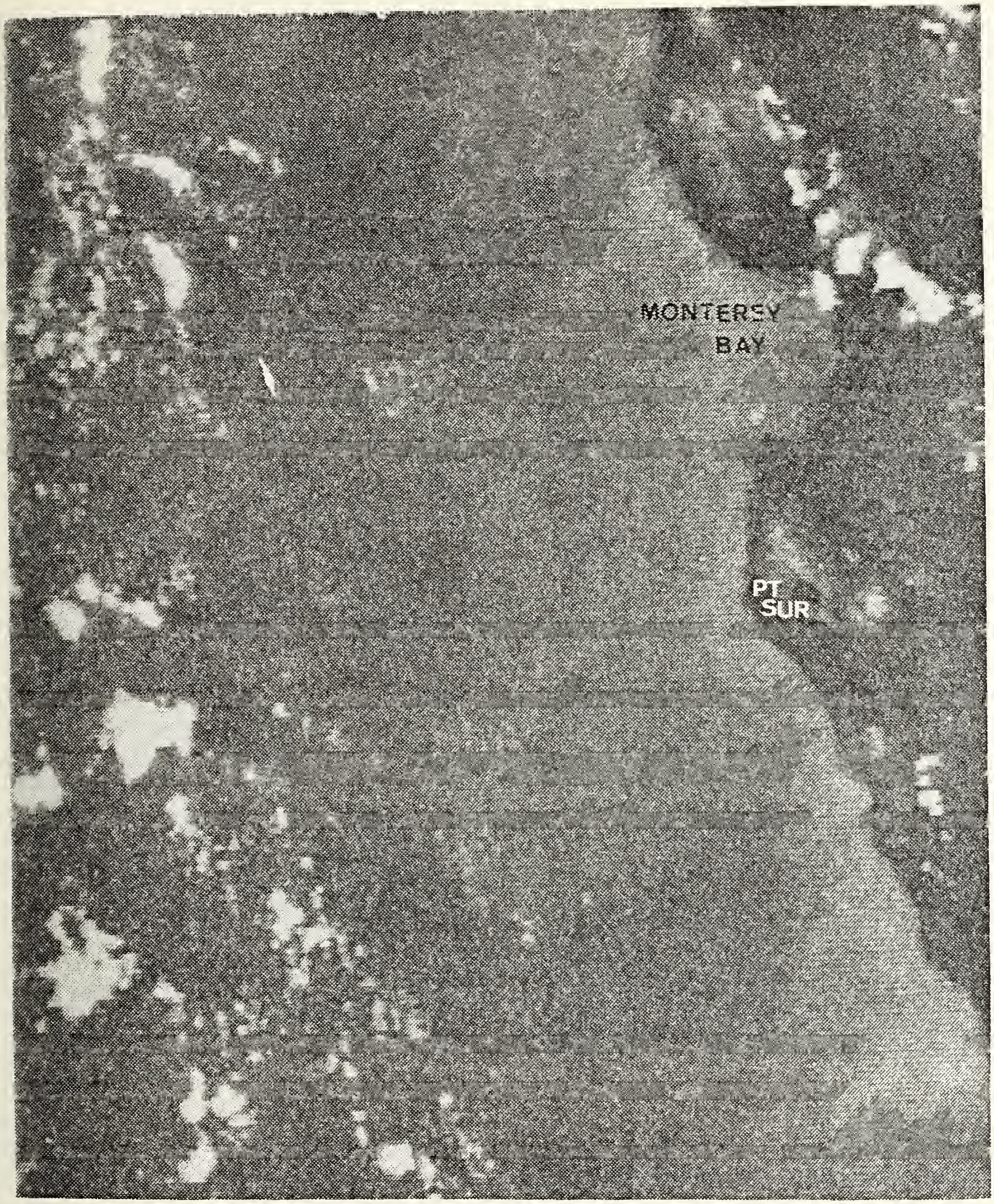

Plate 3. TIROS-N Satellite IR Image of the California Coast, 18 April 1979.

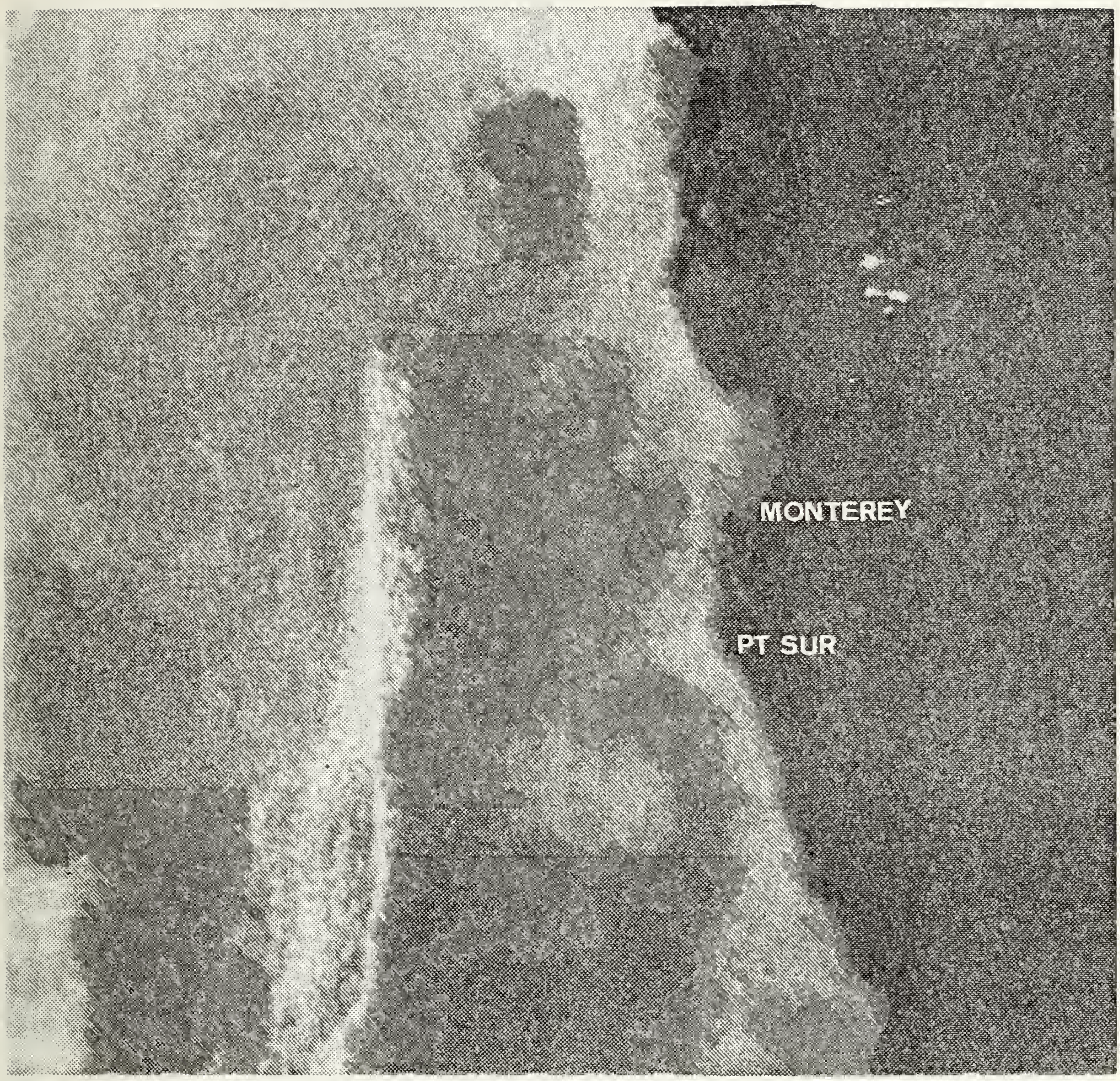

Plate 4. TIROS-N Satellite IR Image of the California Coast, 19 April 1979.

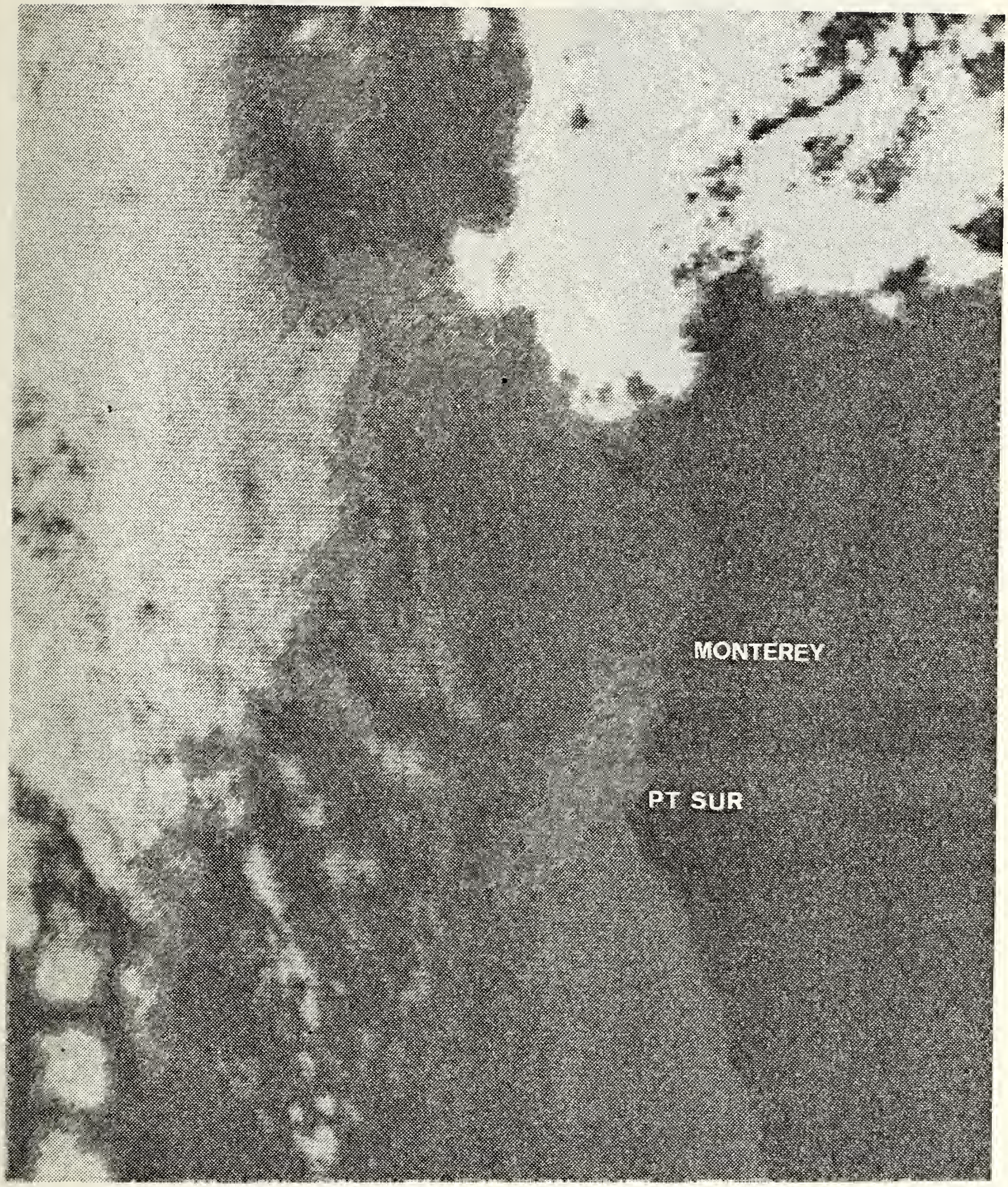

Plate 5. TIROS-N Satellite IR Image of the California Coast, 29 April 1979.

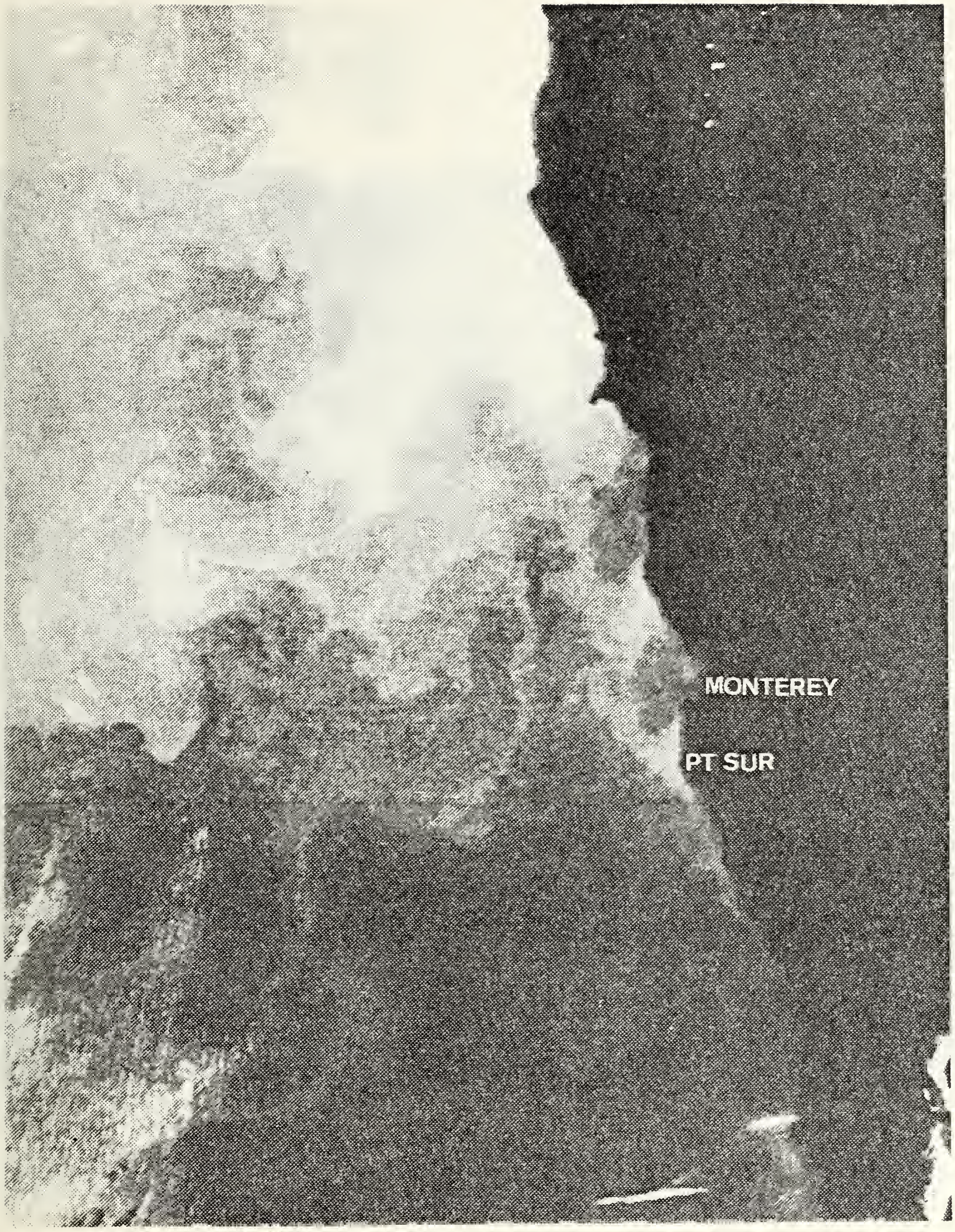

Plate 6. TIROS-N Satellite IR Image of the California Coast, 13 June 1979.

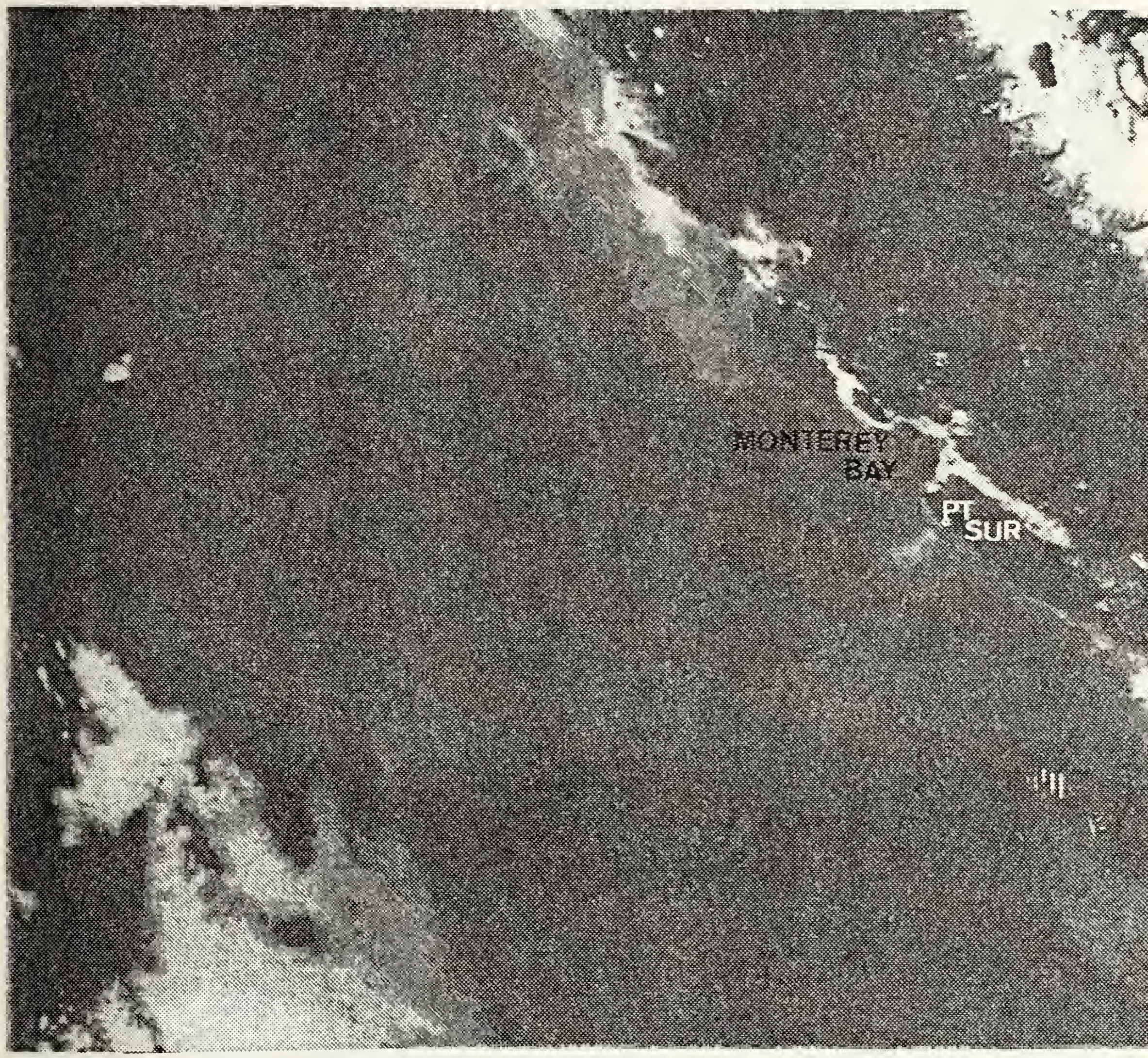

Plate 7. TIROS-N Satellite IR Image of the California Coast, 30 July 1979.

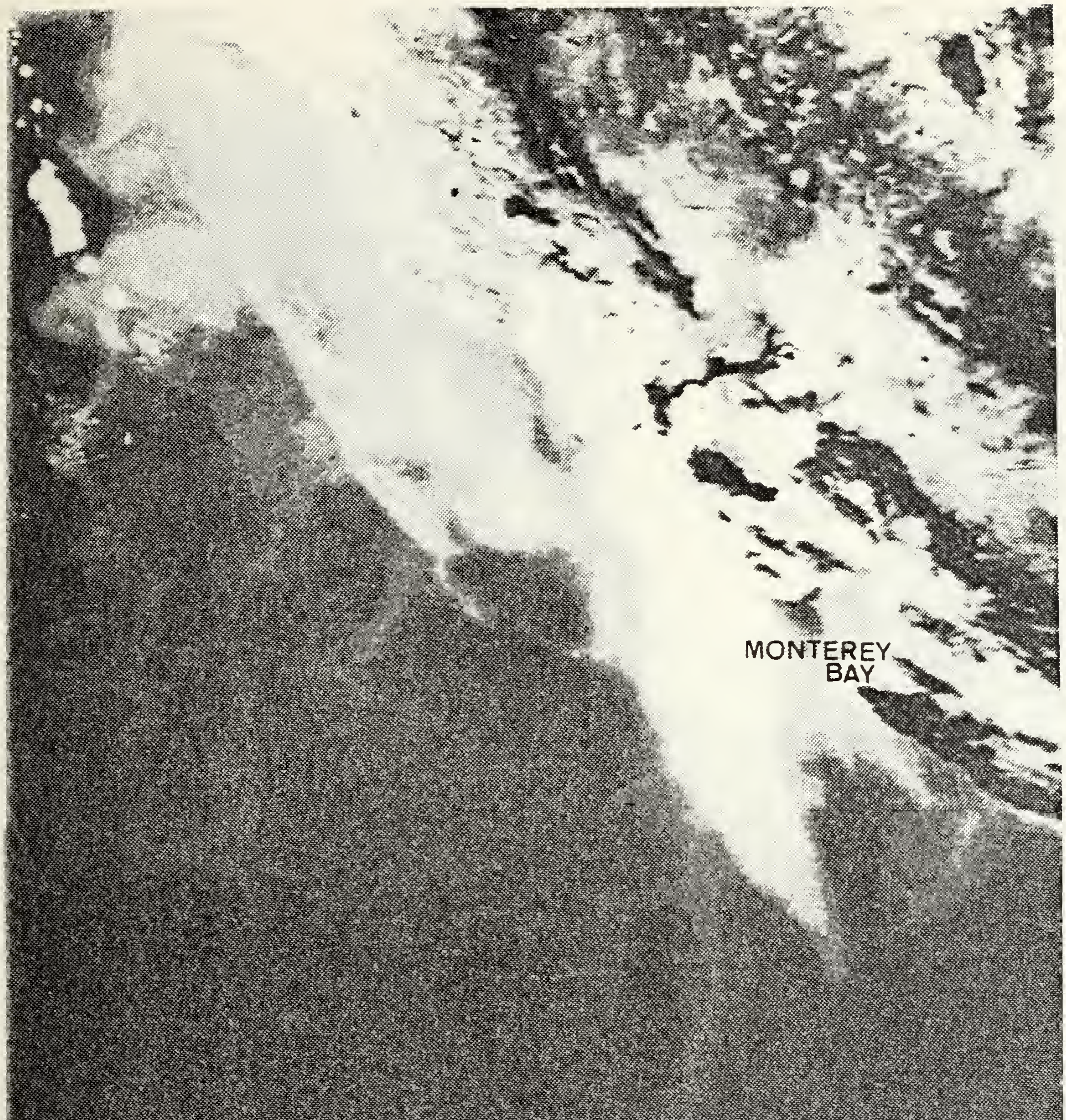

Plate 8. TIROS-N Satellite IR Image of the California Coast, 5 August 1979.

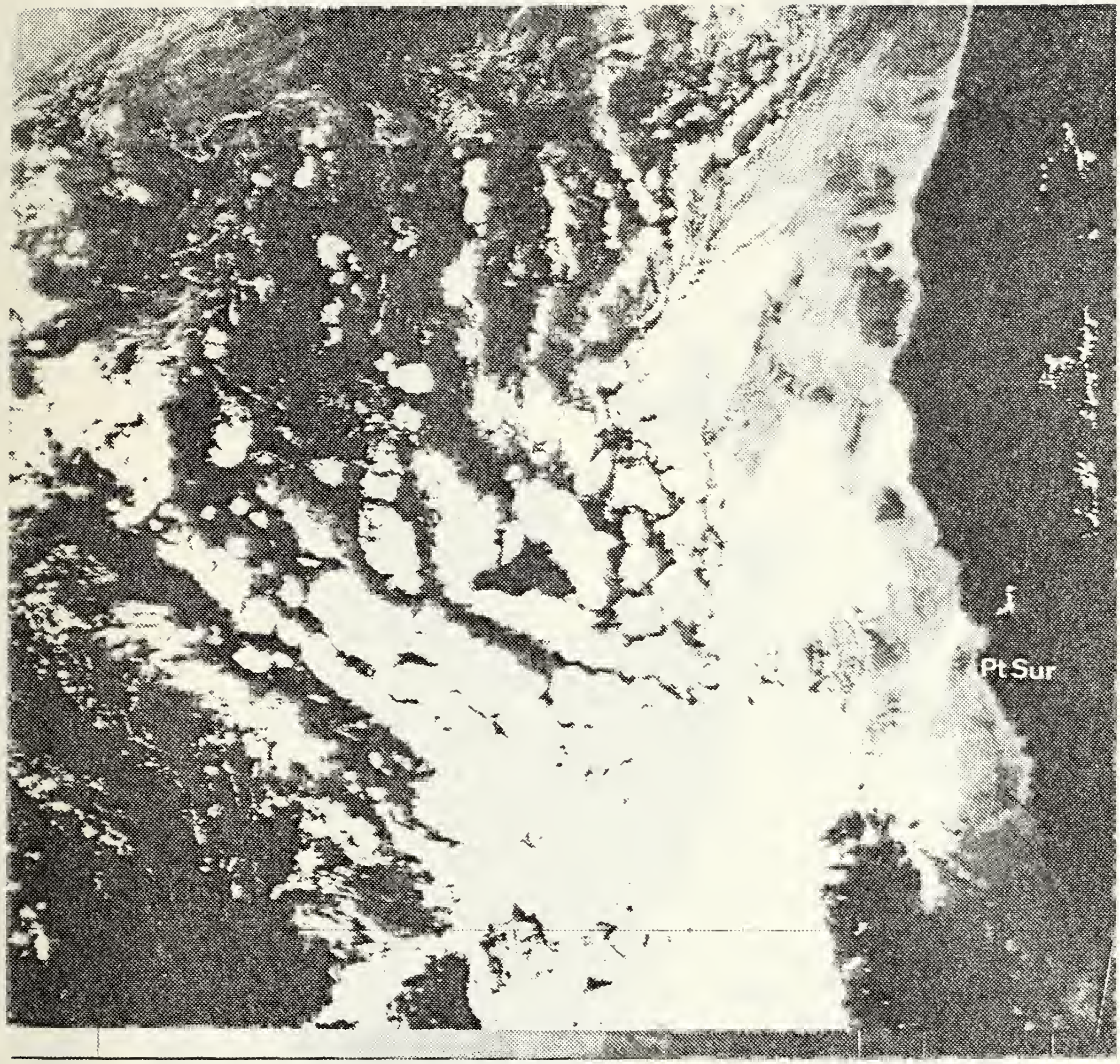

Plate 9. TIROS-N Satellite IR Image of the California Coast, 23 September 1979.

Plate 10. TIROS-N Satellite IR Image of the California Coast, 24 September 1979.

Plate 11. TIROS-N Satellite IR Image of the California Coast, 25 September 1979.

Plate 12. TIROS-N Satellite IR Image of the California Coast, 26 September 1979.

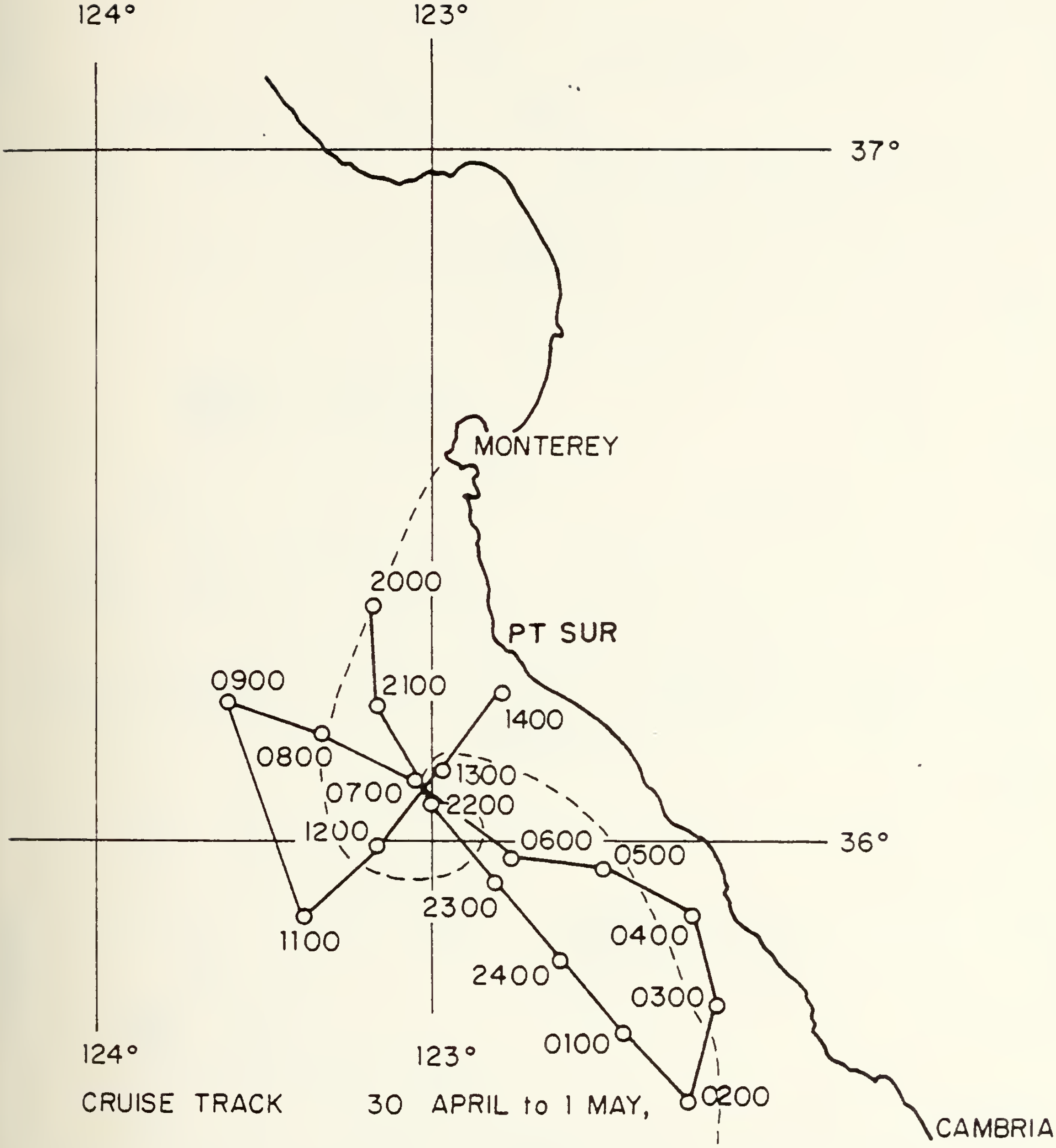

Figure 1. Track of the April '79 Cruise and outline of the upwelling feature based on satellite IR imagery.

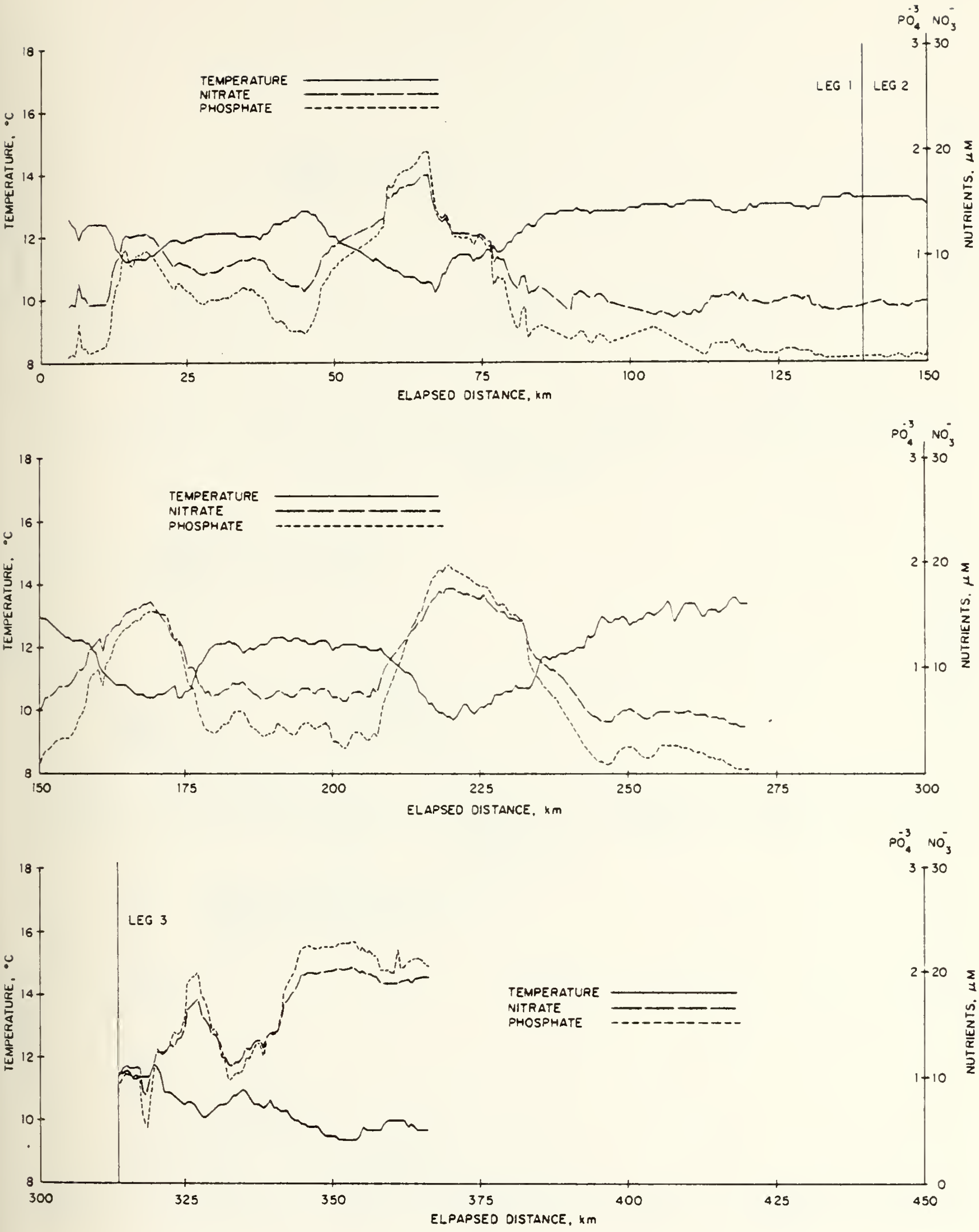

Figure 2. Nitrate, phosphate, and sea surface temperature versus elapsed distance along the track of the April '79 Cruise.

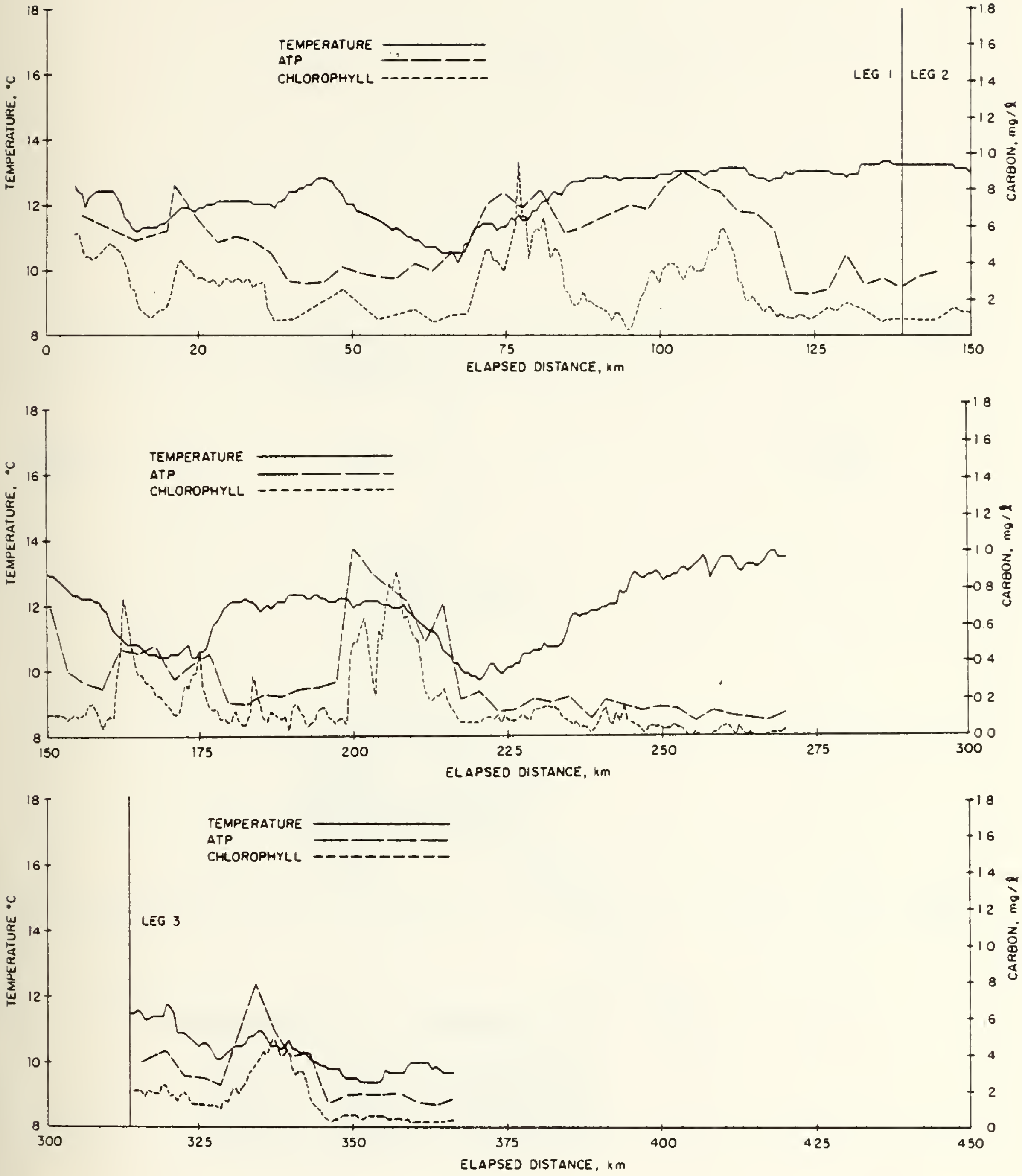

Figure 3. ATP, chlorophyll a, and sea surface temperature versus elapsed distance along the track of the April '79 Cruise.

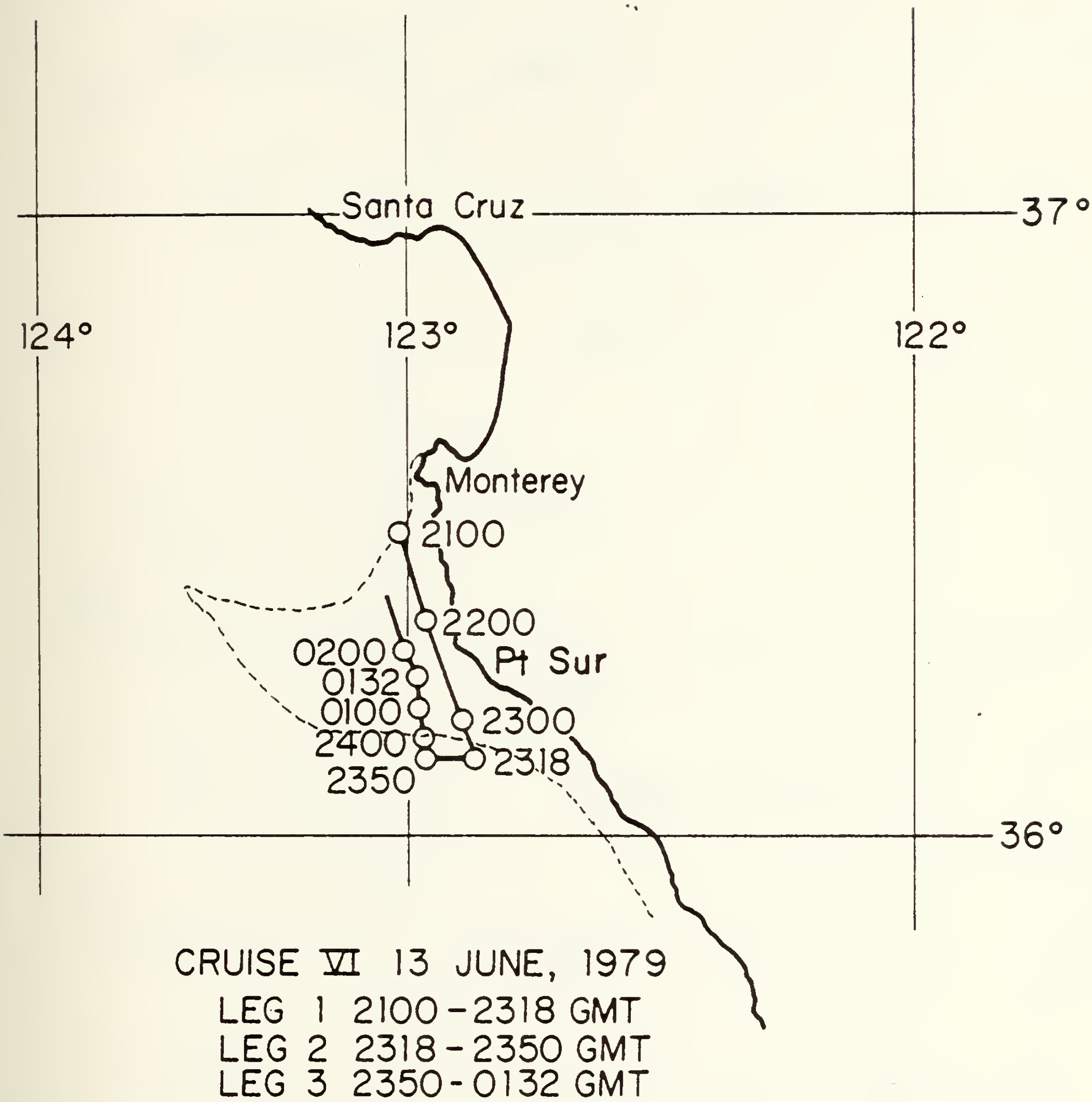

Figure 4. Track of the June '79 Cruise and outline of the upwelling feature based on satellite IR imagery.

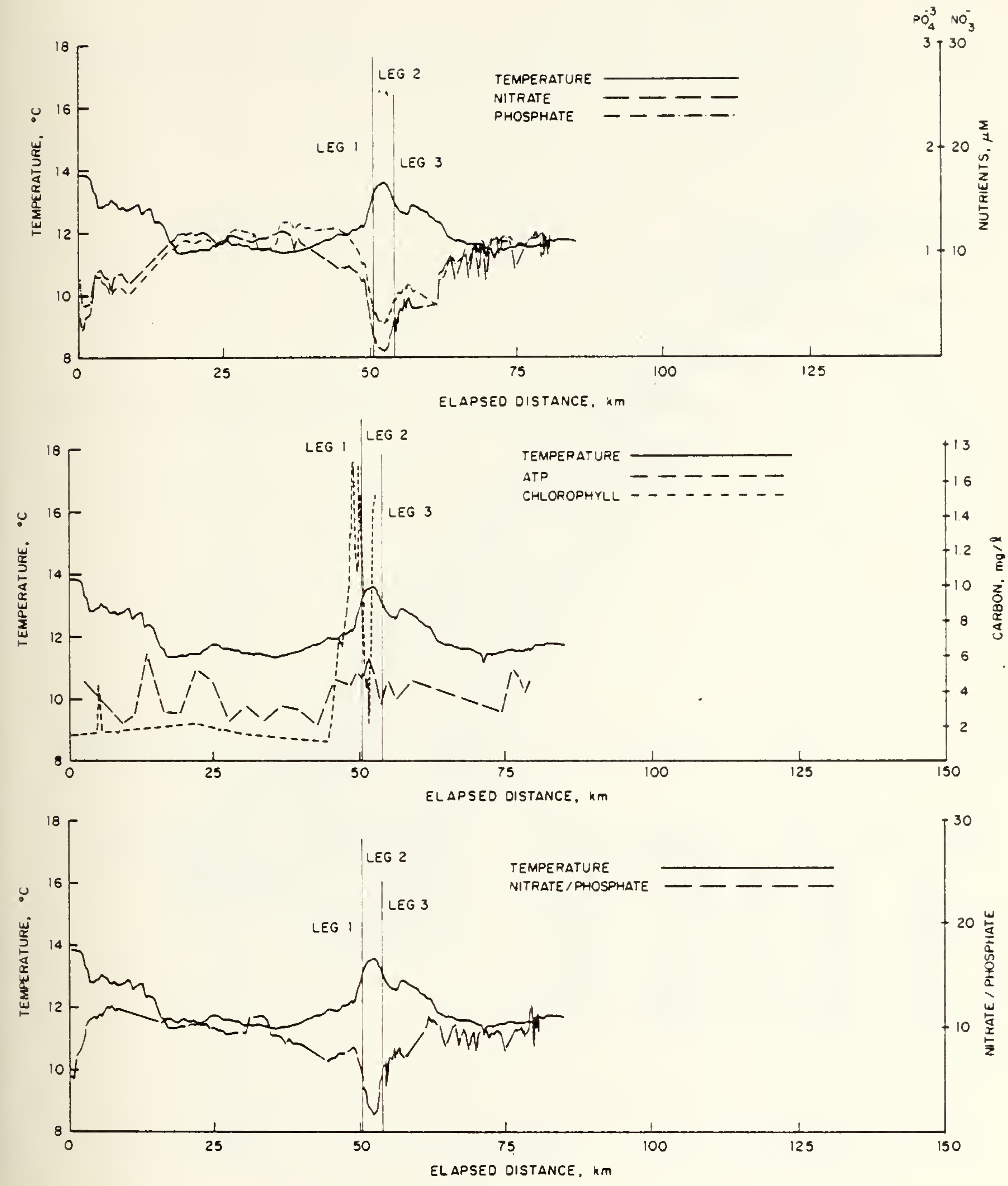

Figure 5. Nitrate, phosphate, nutrient ratio, ATP, chlorophyll a and sea surface temperature versus elapsed distance along track of the June '79 Cruise.

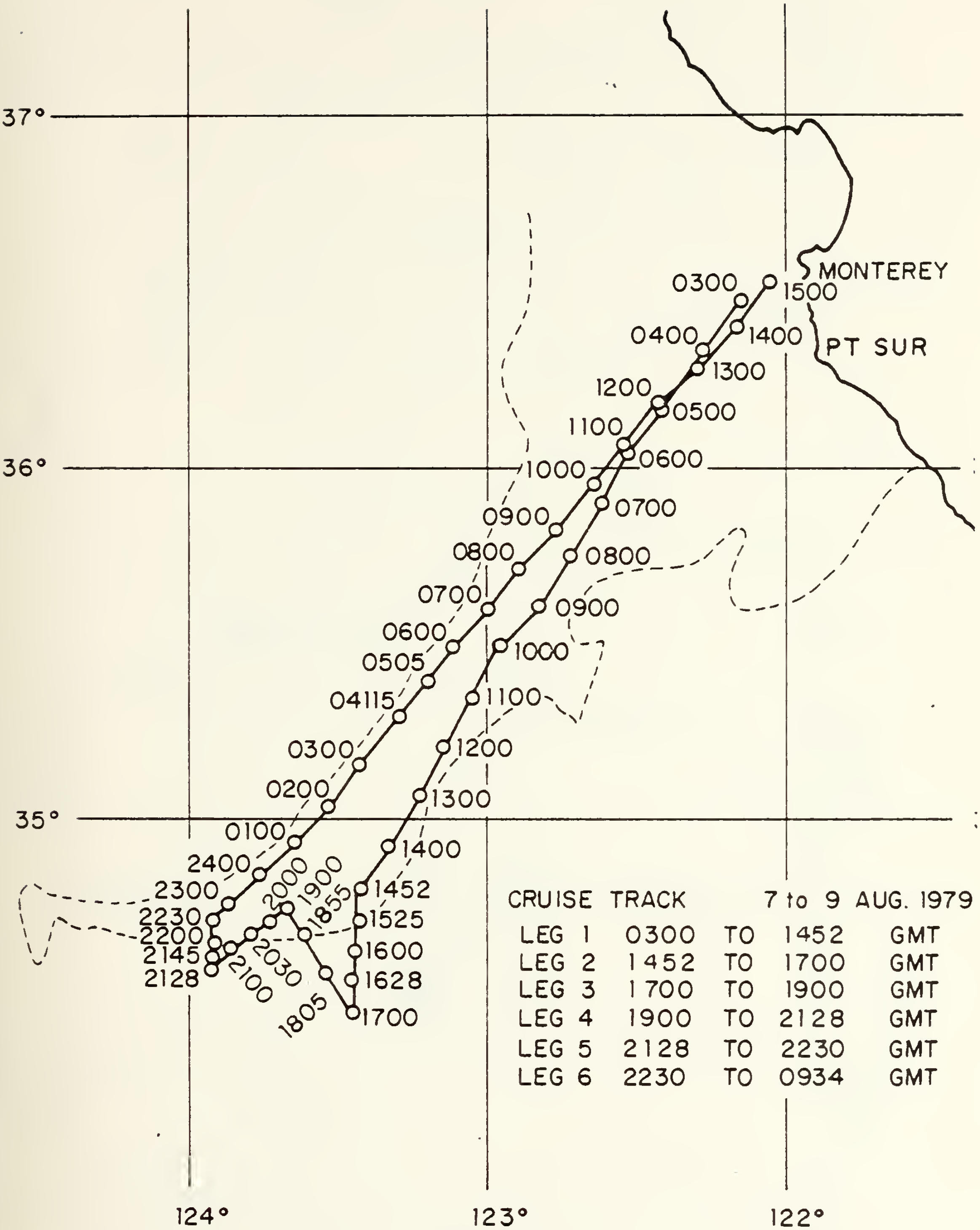

Figure 6. Track of the August '79 Cruise and outline of the upwelling feature based on satellite IR imagery.

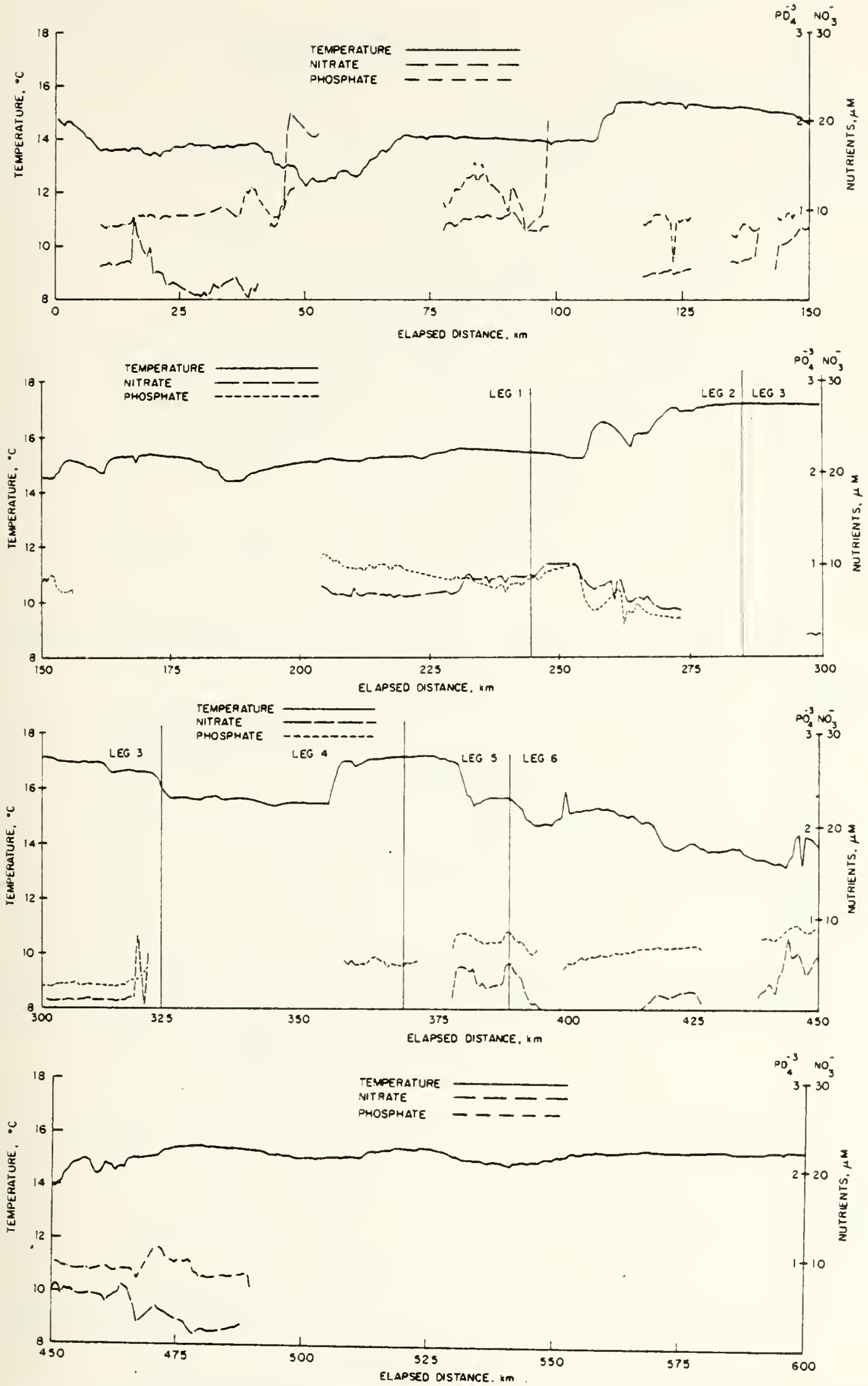

Figure 7. Nitrate, phosphate, and sea surface temperature versus elapsed distance along the track of the August '79 Cruise.

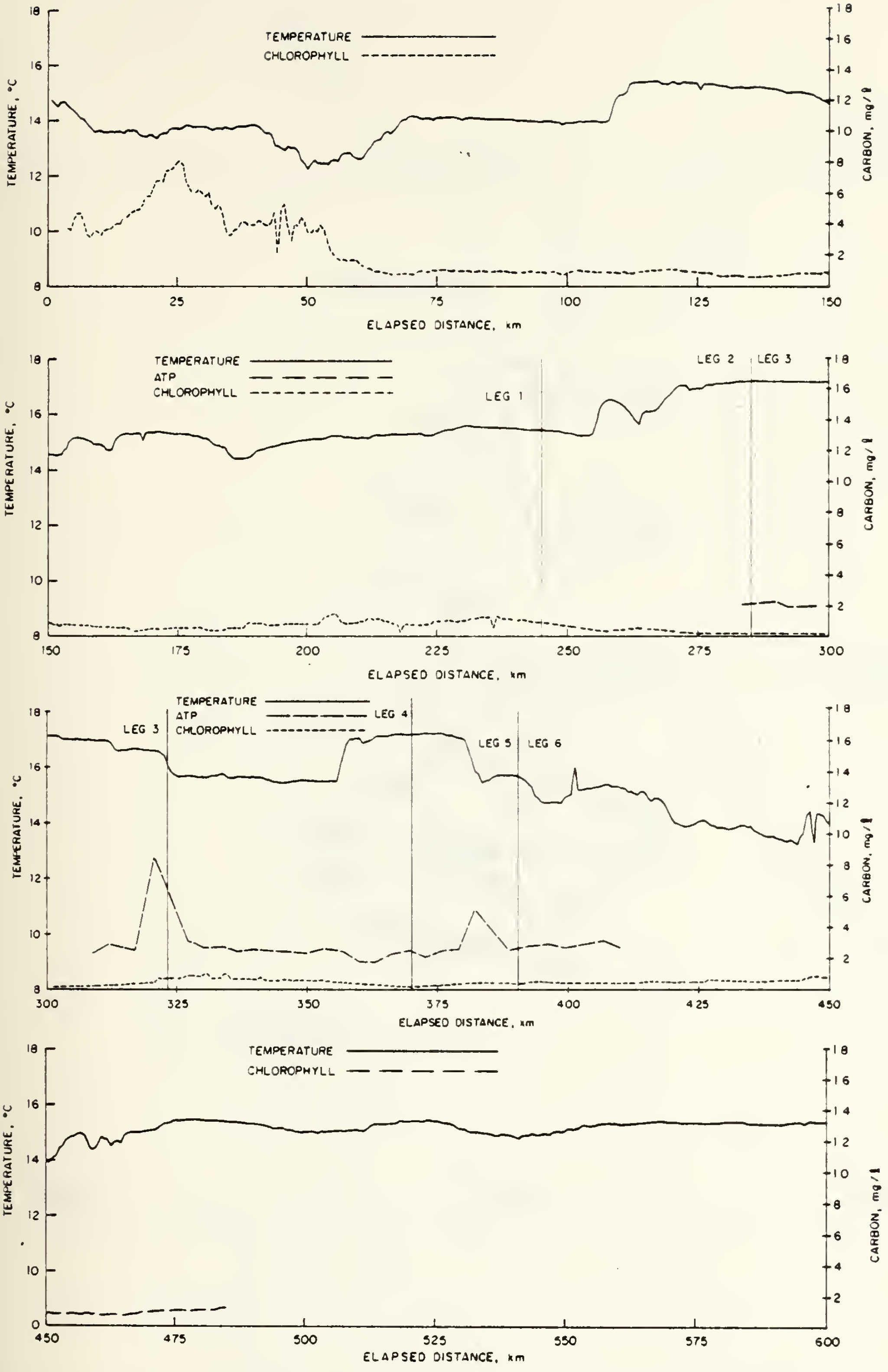

Figure 8. ATP, chlorophyll a and sea surface temperature versus elapsed distance along the track of the August '79 Cruise.

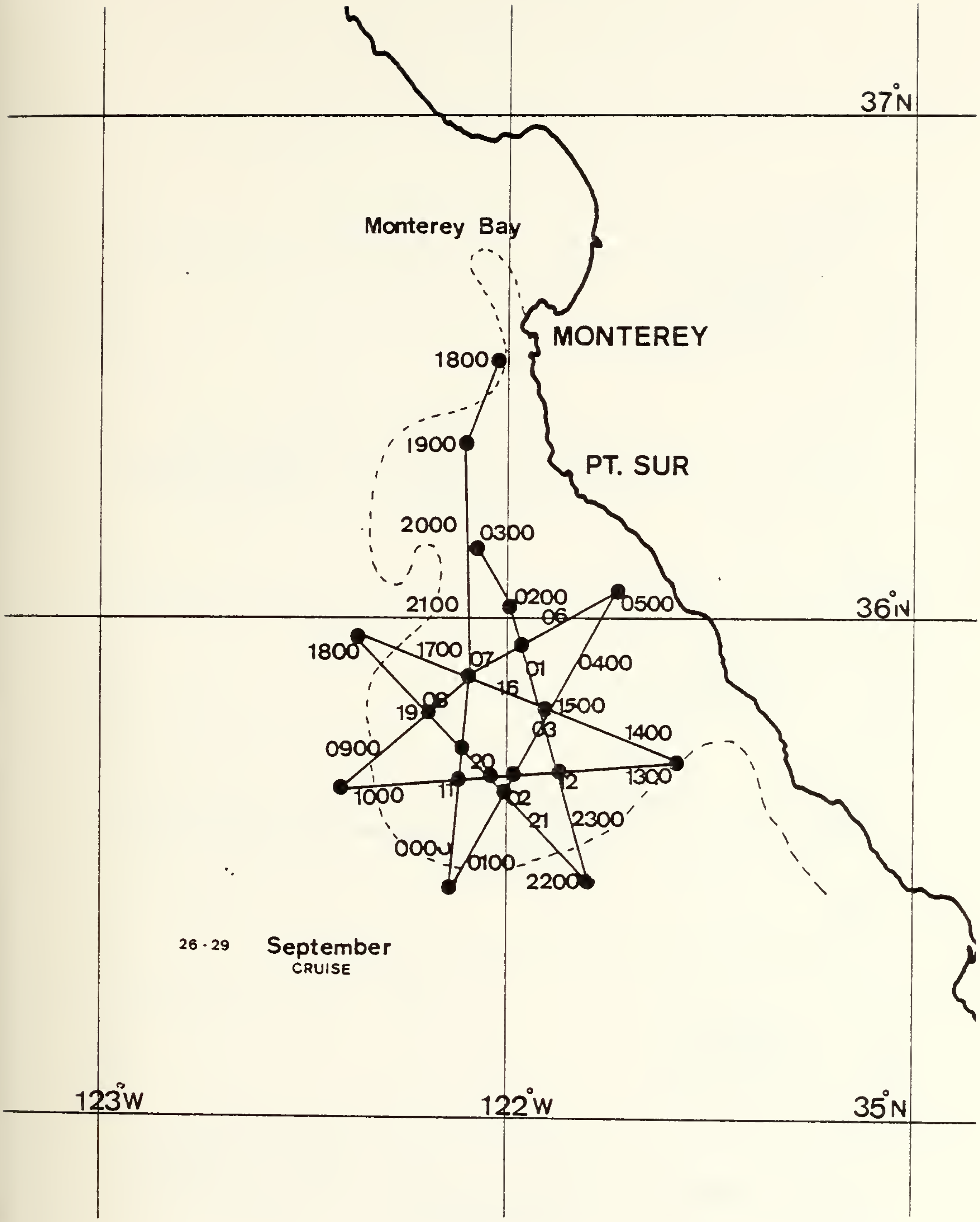

Figure 9. Track of the September '79 Cruise and outline of the upwelling feature based on satellite IR imagery.

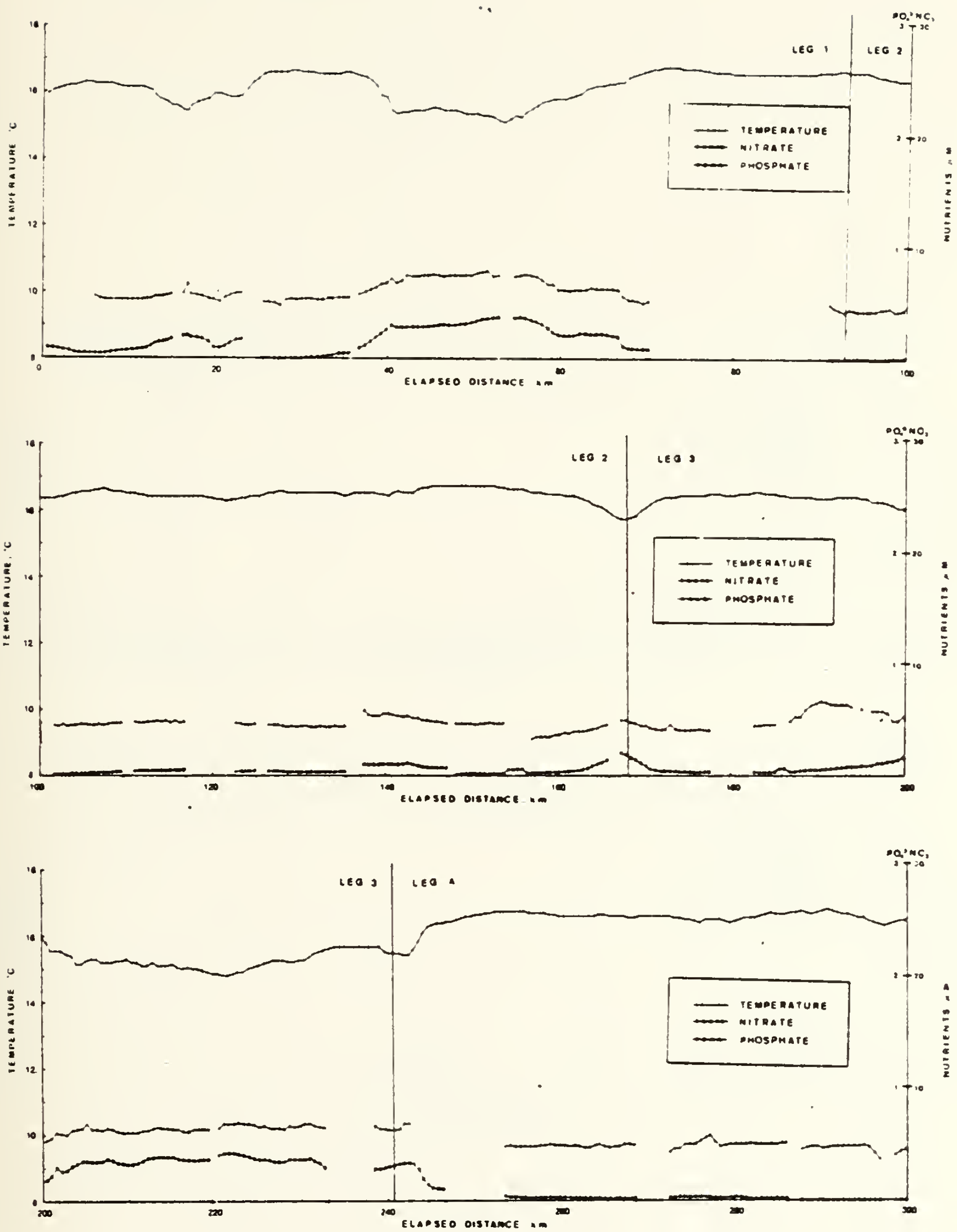

Figure 10. Nitrate, phosphate and sea surface temperature versus elapsed distance along the track of the September '79 Cruise.

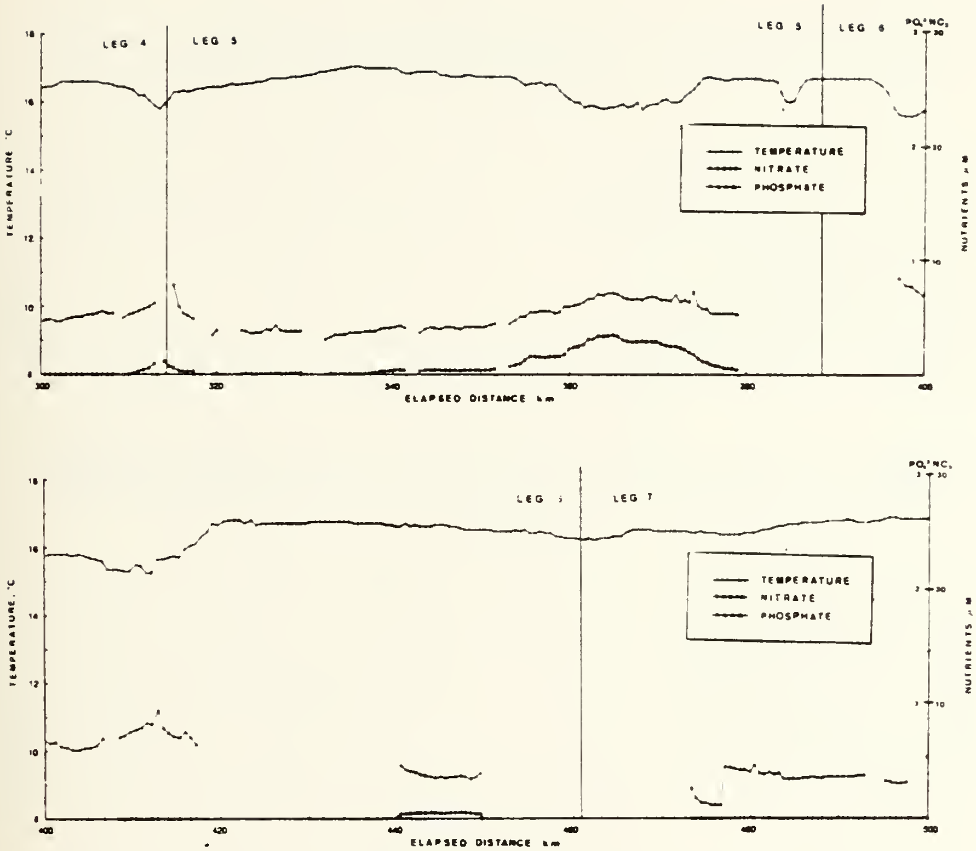

Figure 10. Continued.

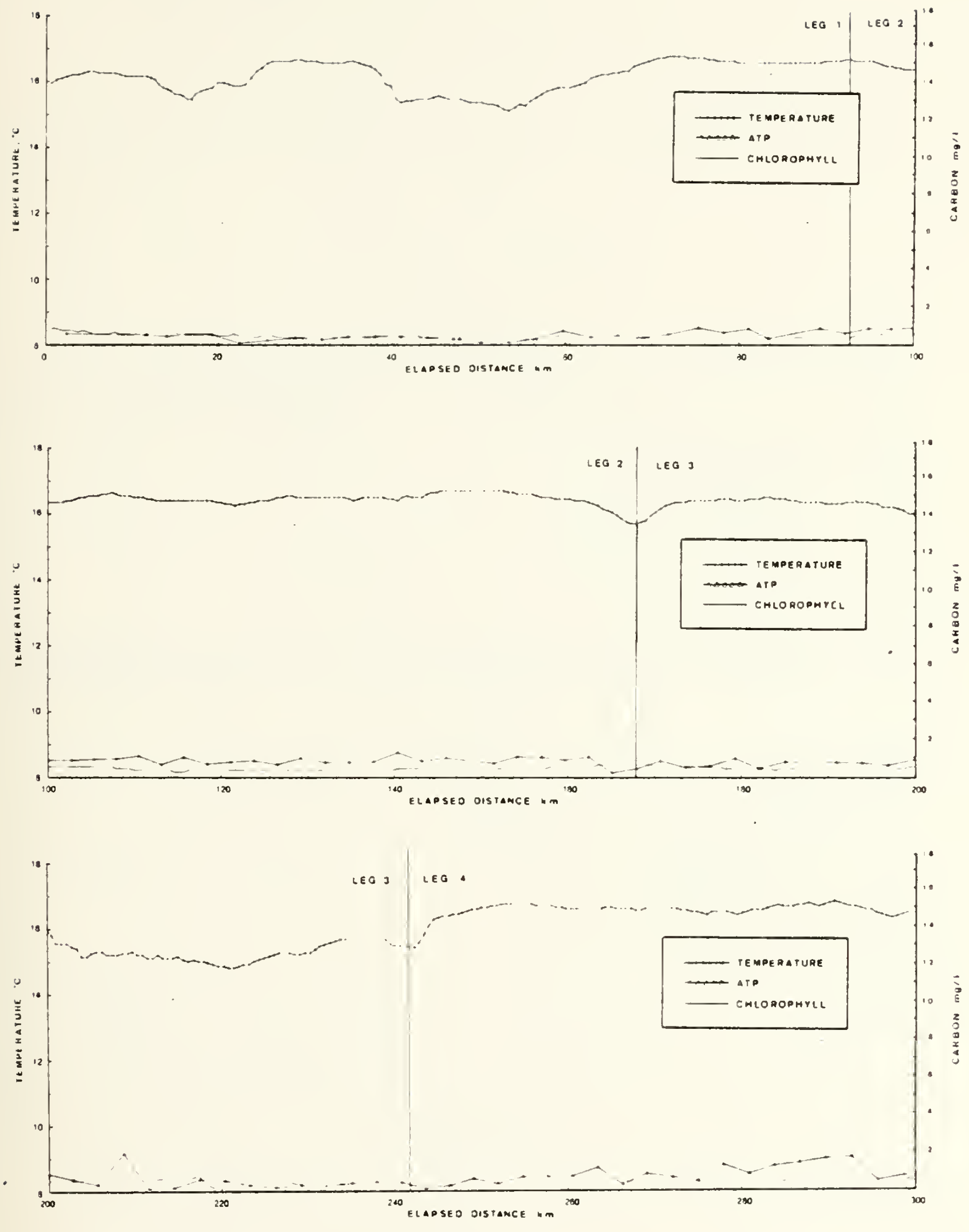

Figure 11. ATP, chlorophyll a and sea surface temperature versus elapsed distance along the track of the September '79 Cruise.

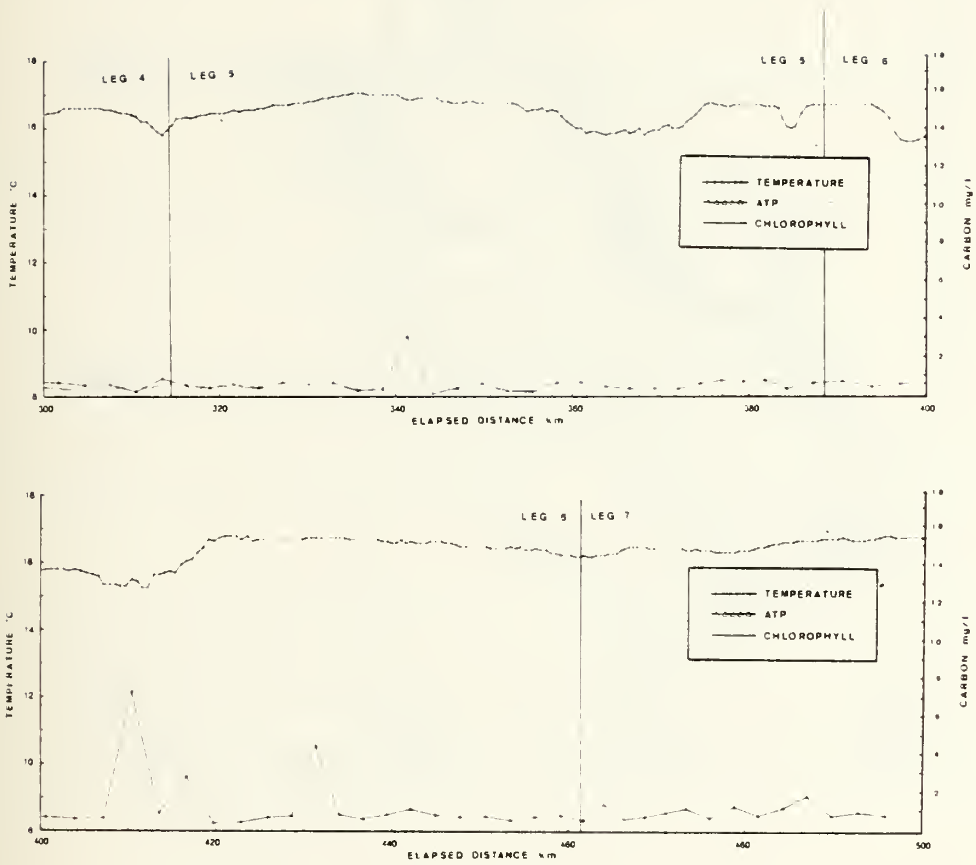

Figure 11. Continued.

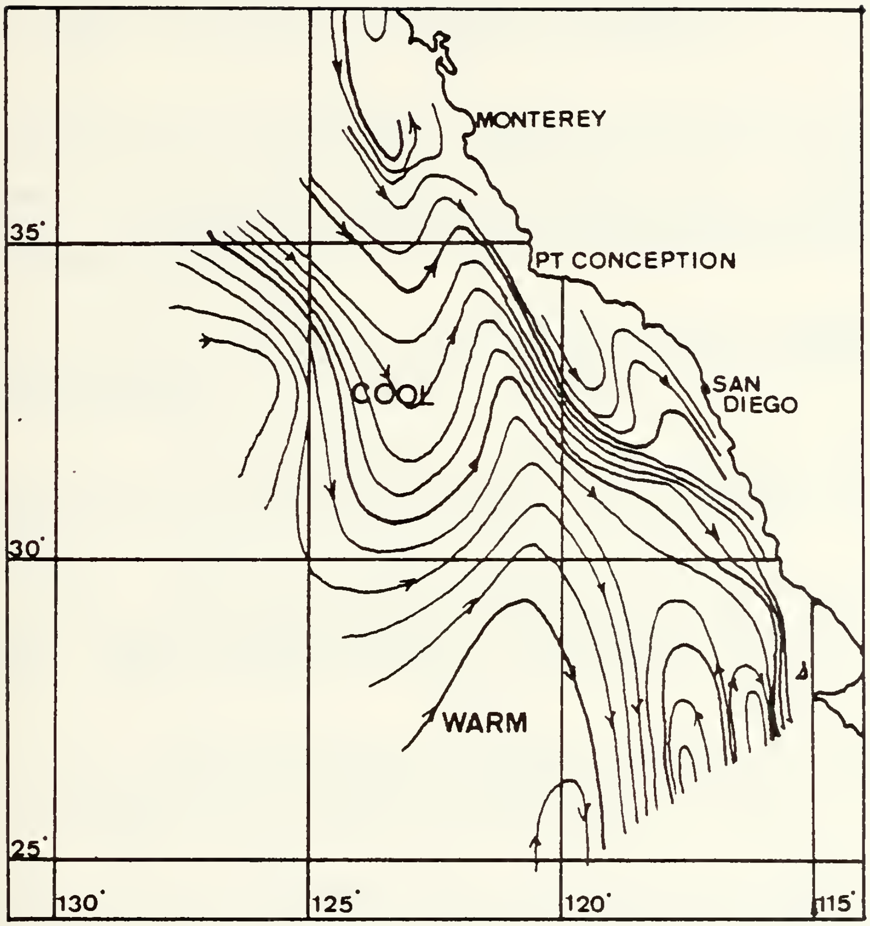

Figure 12. Tongues of cool and warm water alternating away from and towards the coast. (After Sverdrup et al, 1942)

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